Performance comparison between hybridizable DG and classical DG methods for elastic waves simulation in harmonic domain

M. Bonnasse-Gahot[1,2], H. Calandra[3], J. Diaz[1] and S. Lanteri[2]

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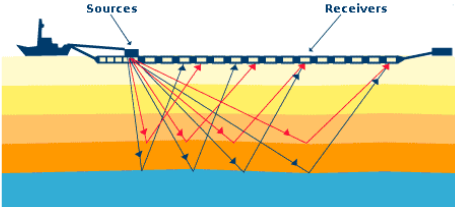
Motivation

Examples of seismic applications



Motivation

Imaging method : the full wave inversion

- Iterative procedure
- Inverse problem requiring to solve a lot of forward problems

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- Time-domain : imaging condition complicated but low computational cost
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Seismic imaging : time-domain or harmonic-domain ?

- Time-domain : imaging condition complicated but low computational cost
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Forward problem of the inversion process

- Elastic wave propagation in harmonic domain : Helmholtz equation
- Reduction of the size of the linear system

Motivation

Seismic imaging in heterogeneous complex media

- Complex topography
- High heterogeneities

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DG method

- Flexible choice of interpolation orders ($p - adaptativity$)
- Highly parallelizable method
- Increased computational cost as compared to classical FEM

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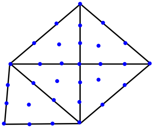
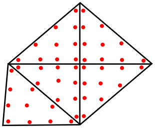


DOF of classical FEM



DOF of DGM

Motivation

Objective of this work

- Development of an hybridizable DG (HDG) method
- Comparison with a reference method : a standard nodal DG method

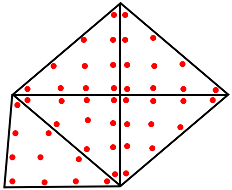


FIGURE : Degrees of freedom of DGM

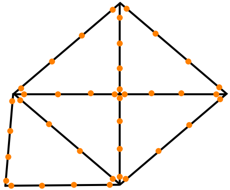


FIGURE : Degrees of freedom of HDGM

HDG methods

HDG methods

- B. Cockburn, J. Gopalakrishnan, R. Lazarov *Unified hybridization of discontinuous Galerkin, mixed and continuous Galerkin methods for second order elliptic problems*, SIAM Journal on Numerical Analysis, Vol. 47 (2009)
- S. Lanteri, L. Li, R. Perrussel, *Numerical investigation of a high order hybridizable discontinuous Galerkin method for 2d time-harmonic Maxwell's equations*, COMPEL, Vol. 32 (2013) (time-harmonic domain)
- N.C. Nguyen, J. Peraire, B. Cockburn, *High-order implicit hybridizable discontinuous Galerkin methods for acoustics and elastodynamics*, J. of Comput. Physics, Vol. 230 (2011) (time domain for seismic applications)

Contents

2D Helmholtz elastic equations

First order formulation of Helmholtz wave equations

$\mathbf{x} = (x, y) \in \Omega \subset \mathbb{R}^2$,

$$\begin{cases} i\omega\rho(\mathbf{x})\mathbf{v}(\mathbf{x}) = \nabla \cdot \underline{\underline{\sigma}}(\mathbf{x}) + f_s(\mathbf{x}) \\ i\omega\underline{\underline{\sigma}}(\mathbf{x}) = \underline{\underline{C}}(\mathbf{x})\ \underline{\underline{\varepsilon}}(\mathbf{v}(\mathbf{x})) \end{cases}$$

- Free surface condition : $\underline{\underline{\sigma}}\mathbf{n} = 0$ on Γ_l
- Absorbing boundary condition : $\underline{\underline{\sigma}}\mathbf{n} = v_p(\mathbf{v} \cdot \mathbf{n})\mathbf{n} + v_s(\mathbf{v} \cdot \mathbf{t})\mathbf{t}$ on Γ_a

- $\mathbf{v}$: velocity vector
- $\underline{\underline{\sigma}}$: stress tensor
- $\underline{\underline{\varepsilon}}$: strain tensor

2D Helmholtz elastic equations

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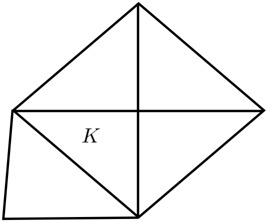
- ρ : mass density
- $\underline{\underline{C}}$: tensor of elasticity coefficients
- v_p : P-wave velocity
- v_s : S-wave velocity
- f_s : source term, $f_s \in L^2(\Omega)$

Contents

Notations and definitions

Notations

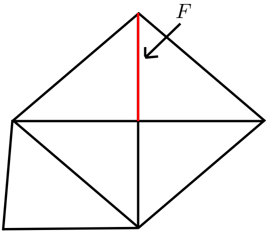
- $\mathcal{T}_h$ mesh of Ω composed of triangles K



Notations and definitions

Notations

- $\mathcal{T}_h$ mesh of Ω composed of triangles K
- $\mathcal{F}_h$ set of all faces F of $\mathcal{T}_h$



Notations and definitions

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- $\mathcal{T}_h$ mesh of Ω composed of triangles K
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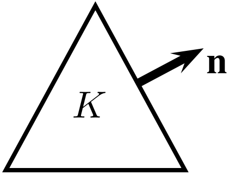
- $\mathbf{n}$ the normal outward vector of an element K



Notations and definitions

Approximations spaces

- $P_p(K)$ set of polynomials of degree at most p on K

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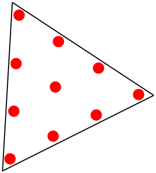

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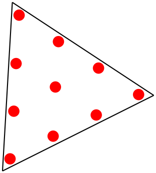

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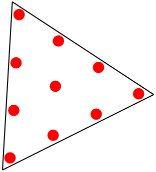
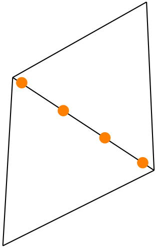
- $\mathbf{M}_h = \{\eta \in \left(L^2(\mathcal{F}_h)\right)^2 : \quad \eta|_F \in (P_p(F))^2, \forall F \in \mathcal{F}_h\}$





Notations and definitions

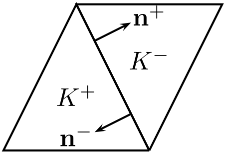
Definitions

- Jump $[\![\cdot]\!]$ of a vector $\mathbf{v}$ through F :

$$[\![\mathbf{v}]\!] = \mathbf{v}^+ \cdot \mathbf{n}^+ + \mathbf{v}^- \cdot \mathbf{n}^- = \mathbf{v}^+ \cdot \mathbf{n}^+ - \mathbf{v}^- \cdot \mathbf{n}^+$$

- Jump of a tensor $\underline{\underline{\sigma}}$ through F :

$$[\![\underline{\underline{\sigma}}]\!] = \underline{\underline{\sigma}}^+ \mathbf{n}^+ + \underline{\underline{\sigma}}^- \mathbf{n}^- = \underline{\underline{\sigma}}^+ \mathbf{n}^+ - \underline{\underline{\sigma}}^- \mathbf{n}^+$$



Contents

HDG formulation of the equations

Local HDG formulation

$$\left\{\begin{array}{rcl} i\omega\rho\mathbf{v} - \nabla\cdot\underline{\sigma} & = & 0 \\ i\omega\underline{\sigma} - \underline{\underline{C}}\,\underline{\varepsilon}(\mathbf{v}) & = & 0 \end{array}\right.$$

HDG formulation of the equations

Local HDG formulation

$$\left\{\begin{array}{l}\displaystyle\int_K i\omega\rho^K \mathbf{v}^K\cdot\mathbf{w} + \int_K \underline{\underline{\sigma}}^K : \nabla\mathbf{w} - \int_{\partial K} \widehat{\underline{\underline{\sigma}}}^{\partial K}\cdot\mathbf{n}\cdot\mathbf{w} = 0\\ \displaystyle\int_K i\omega\underline{\underline{\sigma}}^K : \underline{\underline{\xi}} + \int_K \mathbf{v}^K\cdot\nabla\cdot\left(\underline{\underline{C}}^K\underline{\underline{\xi}}\right) - \int_{\partial K}\widehat{\mathbf{v}}^{\partial K}\cdot\underline{\underline{C}}^K\underline{\underline{\xi}}\cdot\mathbf{n} = 0\end{array}\right.$$

$\widehat{\underline{\underline{\sigma}}}^K$ and $\widehat{\mathbf{v}}^K$ are numerical traces of $\underline{\underline{\sigma}}^K$ and $\mathbf{v}^K$ respectively on ∂K

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Local HDG formulation

$$\begin{cases} \displaystyle\int_K i\omega\rho^K \mathbf{v}^K \cdot \mathbf{w} + \int_K \underline{\underline{\sigma}}^K : \nabla \mathbf{w} - \int_{\partial K} \widehat{\underline{\underline{\sigma}}}^{\partial K} \cdot \mathbf{n} \cdot \mathbf{w} = 0 \\ \displaystyle\int_K i\omega \underline{\underline{\sigma}}^K : \underline{\underline{\xi}} + \int_K \mathbf{v}^K \cdot \nabla \cdot \left(\underline{\underline{C}}^K \underline{\underline{\xi}} \right) - \int_{\partial K} \widehat{\mathbf{v}}^{\partial K} \cdot \underline{\underline{C}}^K \underline{\underline{\xi}} \cdot \mathbf{n} = 0 \end{cases}$$

We define :

$$\begin{array}{lcll} \widehat{\mathbf{v}}^F & = & \lambda^F, & \forall F \in \mathcal{F}_h, \\ \widehat{\underline{\underline{\sigma}}}^{\partial K} \cdot \mathbf{n} & = & \underline{\underline{\sigma}}^K \cdot \mathbf{n} - \tau \mathbf{I} \left(\mathbf{v}^K - \lambda^{\partial K} \right), & \text{on } \partial K \end{array}$$

where τ is the stabilization parameter ($\tau > 0$)

HDG formulation of the equations

Local HDG formulation

We replace $\widehat{\mathbf{v}}^K$ and $\left(\widehat{\underline{\underline{\sigma}}}^K \cdot \mathbf{n}\right)$ by their definitions into the local equations

$$\left\{ \begin{array}{l} \displaystyle\int_K i\omega\rho^K \mathbf{v}^K \cdot \mathbf{w} + \int_K \underline{\underline{\sigma}}^K : \nabla \mathbf{w} - \int_{\partial K} \underline{\underline{\sigma}}^K \cdot \mathbf{n} \cdot \mathbf{w} \\ \displaystyle\qquad\qquad\qquad\qquad + \int_{\partial K} \tau \mathbf{I} \left(\mathbf{v}^K - \lambda^{\partial K}\right) \cdot \mathbf{w} = 0 \\ \displaystyle\int_K i\omega\underline{\underline{\sigma}}^K : \underline{\underline{\xi}} + \int_K \mathbf{v}^K \cdot \nabla \cdot \left(\underline{\underline{C}}^K \underline{\underline{\xi}}\right) - \int_{\partial K} \lambda^{\partial K} \cdot \underline{\underline{C}}^K \underline{\underline{\xi}} \cdot \mathbf{n} = 0 \end{array} \right.$$

HDG formulation of the equations

Local HDG formulation

$$\begin{cases} \displaystyle\int_K i\omega\rho^K \mathbf{v}^K \cdot \mathbf{w} - \int_K \left(\nabla \cdot \underline{\underline{\sigma}}^K\right) \cdot \mathbf{w} + \int_{\partial K} \tau \mathbf{I} \left(\mathbf{v}^K - \lambda^{\partial K}\right) \cdot \mathbf{w} = 0 \\ \displaystyle\int_K i\omega\underline{\underline{\sigma}}^K : \underline{\underline{\xi}} + \int_K \mathbf{v}^K \cdot \nabla \cdot \left(\underline{\underline{C}}^K \underline{\underline{\xi}}\right) - \int_{\partial K} \lambda^{\partial K} \cdot \underline{\underline{C}}^K \underline{\underline{\xi}} \cdot \mathbf{n} = 0 \end{cases}$$

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We define :

$$\underline{W}^K = \left(\underline{v_x}^K,\ \underline{v_z}^K,\ \underline{\sigma_{xx}}^K,\ \underline{\sigma_{zz}}^K,\ \underline{\sigma_{xz}}^K\right)^T$$

$$\underline{\Lambda} = \left(\underline{\Lambda}^{F_1},\ \underline{\Lambda}^{F_2}, ...,\ \underline{\Lambda}^{F_{n_f}}\right)^T, \text{ where } n_f = \text{card}(\mathcal{F}_h)$$

Discretization of the local HDG formulation

$$\mathbb{A}^K \underline{W}^K + \mathbb{C}^K \underline{\Lambda} = 0$$

HDG formulation of the equations

Transmission condition

In order to determine λ^K, the continuity of the normal component of $\underline{\underline{\widehat{\sigma}}}^K$ is weakly enforced, rendering this numerical trace conservative :

$$\int_F [\![\underline{\underline{\widehat{\sigma}}}^K \cdot \mathbf{n}]\!] \cdot \eta = 0$$

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Replacing $(\underline{\underline{\widehat{\sigma}}}^K \cdot \mathbf{n})$ and summing over all faces, the transmission condition becomes :

$$\sum_{K \in \mathcal{T}_h} \int_{\partial K} \left(\underline{\underline{\sigma}}^K \cdot \mathbf{n} \right) \cdot \eta - \sum_{K \in \mathcal{T}_h} \int_{\partial K} \tau \mathbf{I} \left(\mathbf{v}^K - \lambda^{\partial K} \right) \cdot \eta = 0$$

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Discretization of the transmission condition

$$\sum_{K \in \mathcal{T}_h} \left[\mathbb{B}^K \underline{W}^K + \mathbb{L}^K \underline{\Lambda}\right] = 0$$

HDG formulation of the equations

Global HDG formulation

$$\left\{\begin{array}{l}
\displaystyle\int_K i\omega\rho^K \mathbf{v}^K \cdot \mathbf{w} - \int_K \left(\nabla \cdot \underline{\underline{\sigma}}^K\right) \cdot \mathbf{w} + \int_{\partial K} \tau \mathbf{I}\left(\mathbf{v}^K - \lambda^{\partial K}\right) \cdot \mathbf{w} = 0 \\
\displaystyle\int_K i\omega\underline{\underline{\sigma}}^K : \underline{\underline{\xi}} + \int_K \mathbf{v}^K \cdot \nabla \cdot \left(\underline{\underline{C}}^K \underline{\underline{\xi}}\right) - \int_{\partial K} \lambda^{\partial K} \cdot \underline{\underline{C}}_K \underline{\underline{\xi}} \cdot \mathbf{n} = 0 \\
\displaystyle\sum_{K \in \mathcal{T}_h} \int_{\partial K} \left(\underline{\underline{\sigma}}^K \cdot \mathbf{n}\right) \cdot \eta - \sum_{K \in \mathcal{T}_h} \int_{\partial K} \tau \mathbf{I}\left(\mathbf{v}^K - \lambda^{\partial K}\right) \cdot \eta = 0
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Global HDG discretization

$$\begin{cases} \mathbb{A}^K \underline{W}^K + \mathbb{C}^K \underline{\Lambda} = 0 \\ \displaystyle\sum_{K \in \mathcal{T}_h} \left[\mathbb{B}^K \underline{W}^K + \mathbb{L}^K \underline{\Lambda}\right] = 0 \end{cases}$$

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Global HDG discretization

$$\begin{cases} \underline{W}^K = -(\mathbb{A}^K)^{-1} \mathbb{C}^K \underline{\Lambda} \\ \sum_{K \in \mathcal{T}_h} \left[\mathbb{B}^K \underline{W}^K + \mathbb{L}^K \underline{\Lambda}\right] = 0 \end{cases}$$

HDG formulation of the equations

Global HDG formulation

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Global HDG discretization

$$\sum_{K \in \mathcal{T}_h} \left[-\mathbb{B}^K (\mathbb{A}^K)^{-1} \mathbb{C}^K + \mathbb{L}^K\right] \underline{\Lambda} = 0$$

Main idea of the algorithm using the HDG formulation

1. Construction of the linear system $\mathbb{M}\underline{\Lambda} = 0$

with $\mathbb{M} = \sum_{K \in \mathcal{T}_h} \left[-\mathbb{B}^K (\mathbb{A}^K)^{-1} \mathbb{C}^K + \mathbb{L}^K \right]$

for $K = 1$ to Nb_{tri} **do**

Compute matrices $\mathbb{B}^K, (\mathbb{A}^K)^{-1}, \mathbb{C}^K$ and $\mathbb{L}^K$

Construction of the corresponding section of $\mathbb{K}$

end for

Main idea of the algorithm using the HDG formulation

1. Construction of the linear system $\mathbb{M}\underline{\Lambda} = 0$
2. Construction of the right hand side $\mathbb{S}$

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3. Resolution $\mathbb{M}\underline{\Lambda} = \mathbb{S}$

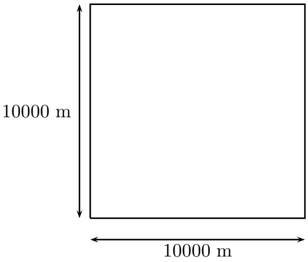
Main idea of the algorithm using the HDG formulation

1. Construction of the linear system $\mathbb{M}\underline{\Lambda} = 0$
2. Construction of the right hand side $\mathbb{S}$
3. Resolution $\mathbb{M}\underline{\Lambda} = \mathbb{S}$
4. Computation of the solutions of the initial problem

for $K = 1$ to Nb_{tri} **do**
  Compute $\underline{W}^K = -(\mathbb{A}^K)^{-1}\mathbb{C}^K\underline{\Lambda}$
end for

Contents

Plane wave



Computational domain Ω setting

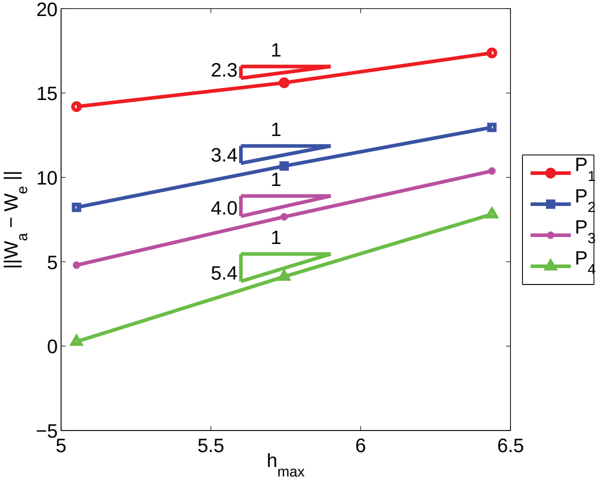
- Physical parameters :
  - $\rho = 2000 kg.m^{-3}$
  - $\lambda = 16 GPa$
  - $\mu = 8 GPa$
- Plane wave :

$$u = \nabla e^{i(k\cos\theta x + k\sin\theta y)}$$

where $k = \dfrac{\omega}{v_p}$

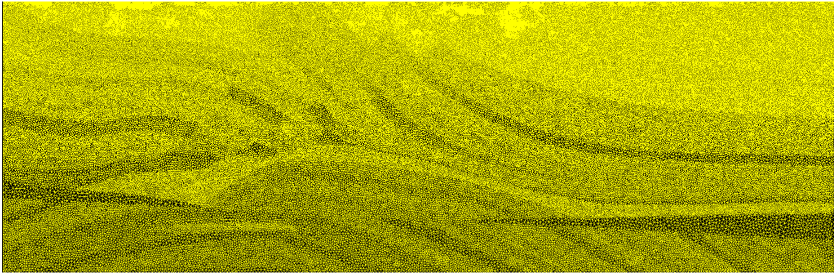
- $\theta = 0$
- Three meshes :
  - 3000 elements
  - 10000 elements
  - 45000 elements

Plane wave



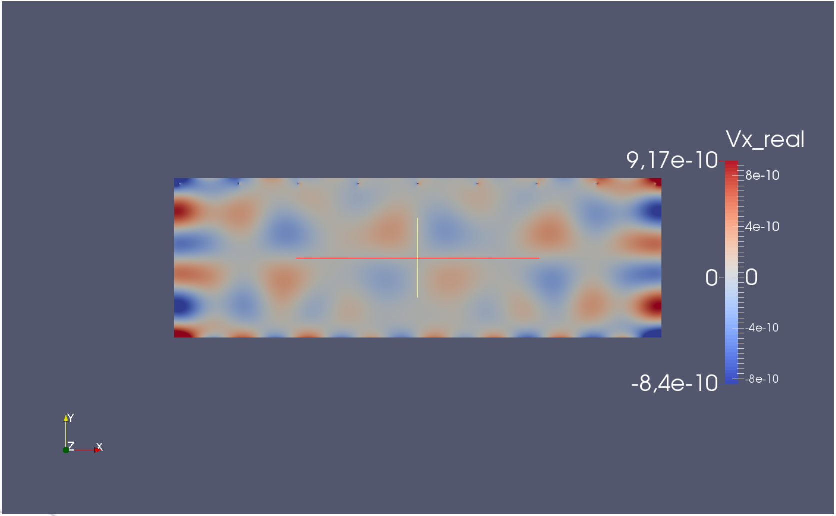
Convergence order of the HDG scheme

Marmousi test-case



Computational domain Ω composed of 235000 triangles

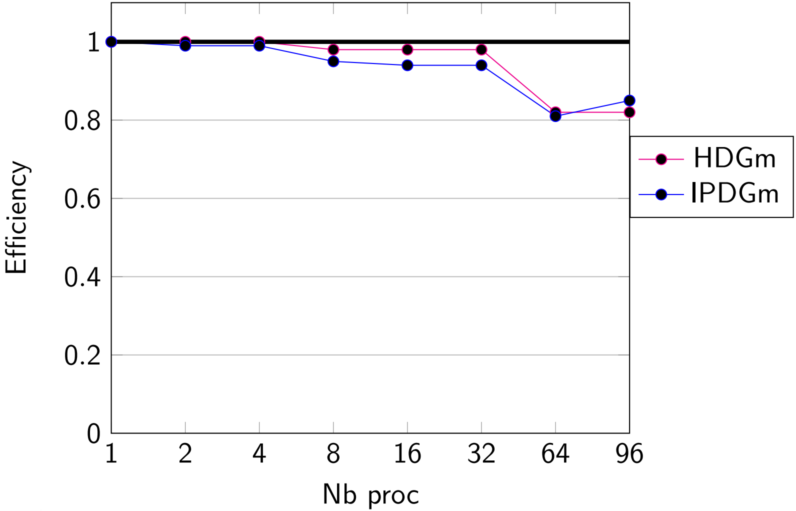
Parallel results for the Marmousi test-case with the HDG-P3 scheme, $f = 2\text{Hz}$



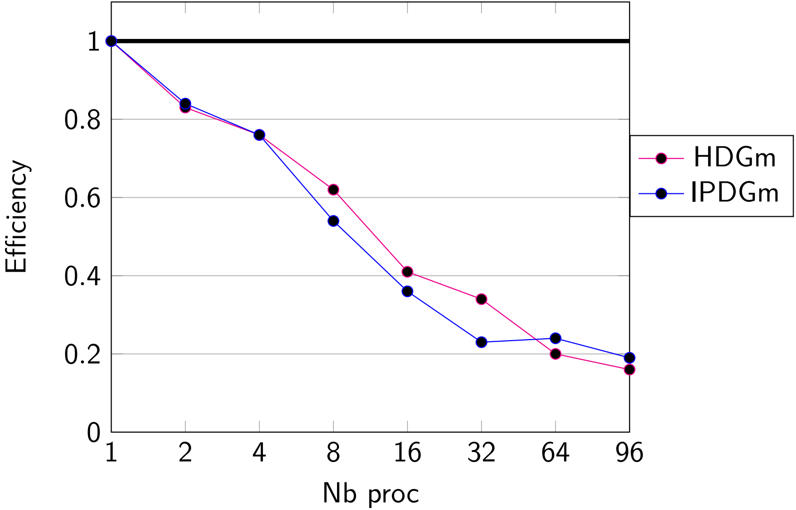
Caracteristics of the computing processors used

- **Plafrim** platform
- Hardware specification : 16 nodes, 12 cores by nodes
- Caracteristics of computing nodes :
  - 2 Hexa-core Westmere Intel® Xeon® X5670
  - Frequency : 2,93 GHz
  - Cache L3 : 12 Mo
  - RAM : 96 Go
  - Infiniband DDR : 20Gb/s
  - Ethernet : 1Gb/s

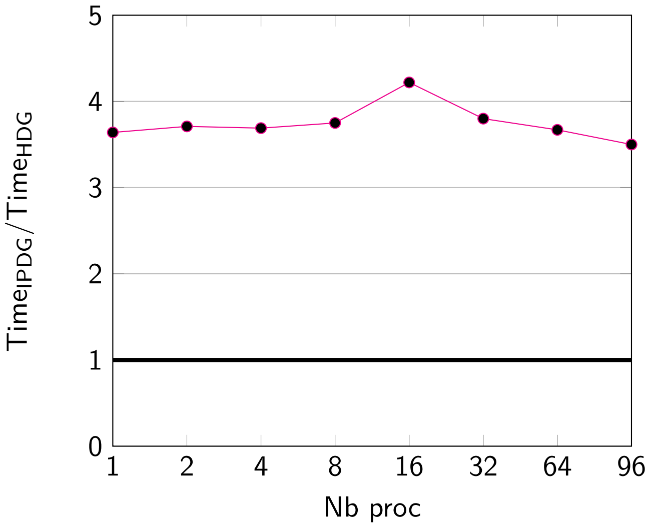
Efficiency of the parallelism of the global matrix construction



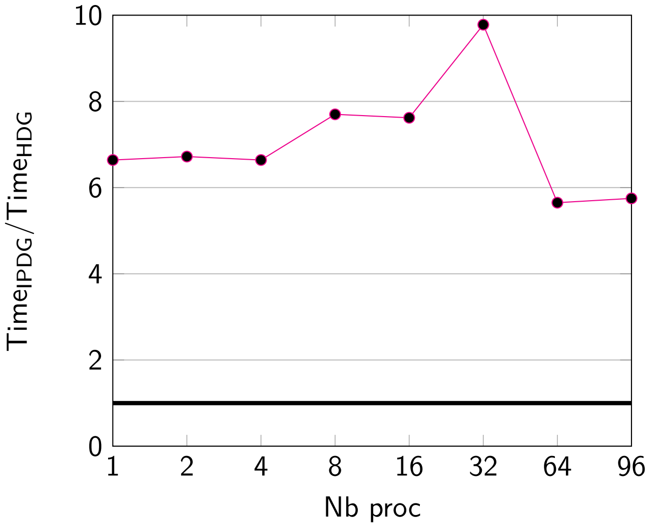
Efficiency of the parallelism of the whole algorithm



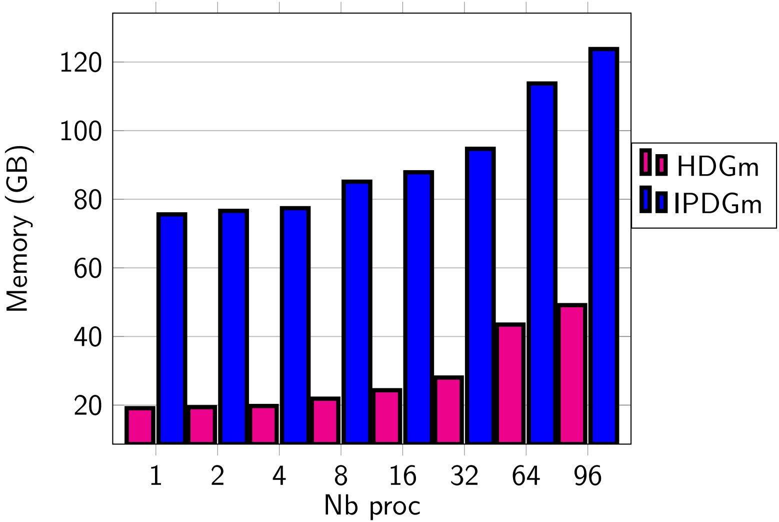
Speed up for the global matrix construction



Speed up (Total simulation time)



Memory required (GB) for the simulation



Contents

Conclusions-Perspectives

Conclusions

On a same mesh, with the HDG method :

- Memory gain
- Computational time gain

Conclusions-Perspectives

Conclusions

On a same mesh, with the HDG method :

- Memory gain
- Computational time gain

Perspectives

- Develop 3D HDG formulation for Helmholtz equations
- Solution strategy for the HDG linear system

Thank you !